

Star Formation Around Active Galactic Nuclei

William C. Keel
 Sterrewacht Leiden
 Leiden, The Netherlands

Emission-line images and high-dispersion optical spectra have been used to investigate star-forming regions in the vicinity of active galactic nuclei, including objects covering a wide range in luminosity of the central source. Rings of HII regions around the nucleus on 100-500 pc scales occur preferentially in galaxies with active nuclei, perhaps indicating a common response to gas flow in certain potential shapes. Multiaperture spectra of nearby HII-region nuclei shows many to have centrally condensed LINER-like components, suggesting that such configuration may be quite common.

The stellar population, and its history, may be probed in some of the most favorable cases. Observed stellar absorption features and crude starburst models imply ages $\sim 10^8$ years and $< 3 \times 10^7$ years for the starbursts around the nuclei of NGC 1068 and 7469, respectively. These are in rough concordance with lifetimes of the nuclear activity based on radio structures; if a direct link between nuclear activity and surrounding starbursts can be demonstrated, this could become an important way to study the history of individual objects. A somewhat different situation is found in Mkn 231, where the whole galaxy (merger?) exhibits optical colors and spectra suggesting either an IMF deficient in OB stars or a sudden turnoff of star formation, on scales so large that it is unlikely the nucleus is directly responsible. There thus appears to be evidence of at least two kinds of links between AGN and star formation.

Active galactic nuclei (Seyfert nuclei and their relatives, in which nonstellar sources of energy are important) and intense star formation can both deliver substantial amounts of energy to the vicinity of a galactic nucleus. Many luminous nuclei have energetics dominated by one of these mechanisms, but detailed observations show that some have a mixture. Seeing both phenomena at once raises several interesting questions:

- 1) Is this a general property of some kinds of nuclei? How many AGNs have surrounding starbursts, and vice versa?
- 2) As in 1), how many undiscovered AGNs or starbursts are hidden by a more luminous instance of the other?
- 3) Does one cause the other, and by what means, or do both reflect common influences such as potential-well shape or level of gas flow?
- 4) Can surrounding star formation tell us anything about the central active nuclei, such as lifetimes, kinetic energy output, or mechanical disturbance of the ISM?

These are important, and perhaps crucial, points in our understanding of activity and star formation in galactic nuclei. Unfortunately, the

observational ways of addressing them are as yet not well formulated. I report here some preliminary studies aimed at clarifying at least the issues involved in study of the relationships between stellar and nonstellar excitement in galactic nuclei.

HII Rings and Active Nuclei

Many spirals, particularly of intermediate Hubble type, show substructures in the nuclear region often termed "hot spots" (e.g. Sersic and Pastoriza 1967). A large fraction of these show a very regular morphology upon more detailed study: a nucleus with late-type (old) stellar population and Seyfert or LINER emission spectrum, surrounded by an elliptical ring of luminous giant HII regions. Such rings may be associated with inner resonances in the stellar orbits (see, for example, Sanders and Huntley 1976, Sanders and Tubbs 1980). Relatively few such objects are known; at the redshifts of even most Markarian Seyferts, they would be blended with the nucleus in ground-based observations. Galaxies in which this morphology is well-established are listed in Table 1 (after Hummel, van der Hulst, and Keel 1986). Note that only one of these (NGC 5427) does not appear in the lists of Sersic and Pastoriza. Typical appearances of these are illustrated in Figure 1, by an H α image of the nucleus of NGC 5248 (from the KPNO 2.1-m with TI CCD).

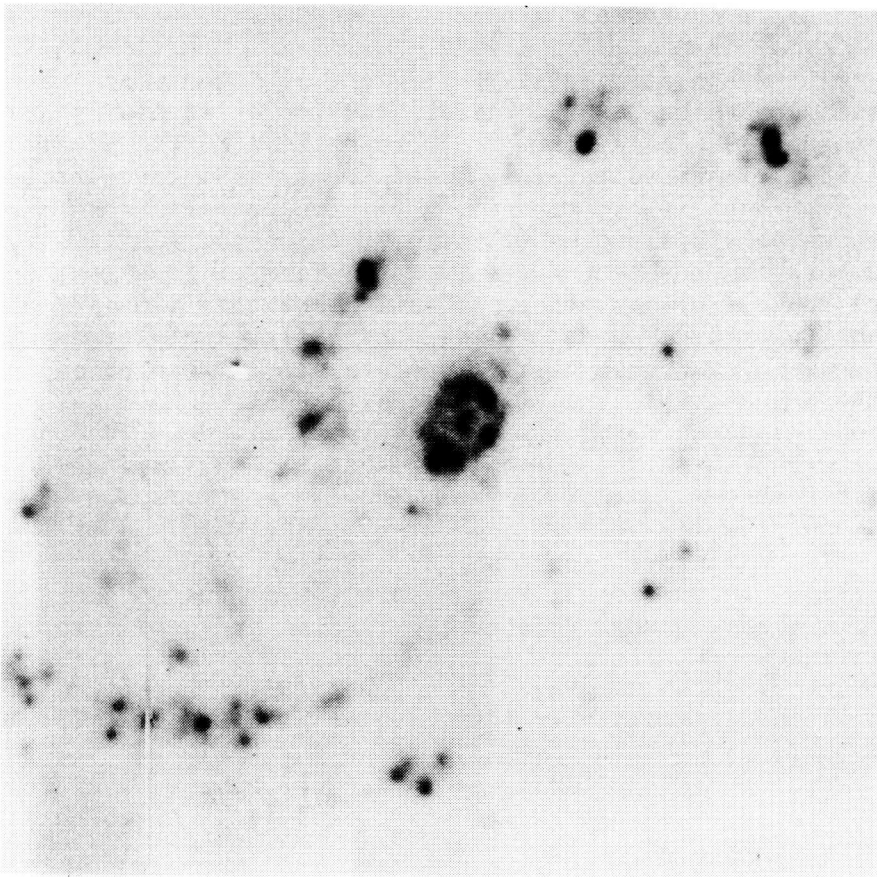
TABLE 1

Galactic Nuclei with HII Rings

NGC	Ring Diameter (kpc)	Nucleus	Hubble Type
1097	1.1	LINER/Sy2	SBb
2297	0.4	LINER?	SABc
3351	0.4	LINER	SBb
4303	0.3	LINER/Sy2	SABbc
4321	1.4	LINER/Sy2	SABbc
5236	0.3	HII	SABc
5248	0.7	LINER	SABbc
5427	1.9	Sy2	Sc

From the data summarized in Table 1, it appears that galaxies with nuclear rings of HII regions are more likely to have indicators of nuclear activity (Seyfert or LINER spectra) than the norm for the Hubble types involved.¹ Particularly noteworthy is the presence of such activity even in

¹The LINERS here are not the "blue LINERS" that are often associated with starbursts (Rieke, these proceedings); the nuclei here (except the HII nucleus of M83) show no real evidence of current star formation inside the HII rings.



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 1. Continuum-subtracted $H\alpha$ + [NII] image of the nuclear region of NGC 5248. The ring of HII regions around the actual nucleus is evident. The field is 160" square, with north at the top.

Sc galaxies, in which it is rare among magnitude-limited samples (e.g. Keel 1983). The available sample clearly points to some kind of connection between HII rings and nuclear activity, both perhaps formed by certain kinds of potential shapes that induce radial gas motion. Complete surveys of the incidence of such rings and properties of the associated nuclei will be important, but can be complicated by several effects. The resolution effect mentioned above means that present data would have difficulty finding such configurations at the distances characteristic of very luminous Seyferts; in such cases, spectroscopic identification of an HII-region component or use of IR colors to infer a star forming region might be possible, but difficult due to the great luminosity of the nucleus. Second, in such very active objects, some of the signatures of HII rings can be lost. In the type 2 Seyfert NGC 5728 (M. M. Phillips *et al.*, private communication) there is dynamical evidence of a gas ring, but its ionization is dominated by radiation from the nucleus. Very detailed study is needed for such objects; more HII rings will likely emerge from detailed studies of individual active nuclei.

Histories of Star-Forming Regions around Seyfert Nuclei

The presence of "starburst disks" - regions of intense star formation on scales of a few kiloparsecs is well established for a few nearby Seyferts. They may be recognized from emission-line properties (Morris *et al.* 1985, Alloin *et al.* 1983), infrared mapping (Cutri *et al.* 1984), and radio-source morphology (A. S. Wilson, these proceedings). The properties of these regions are of interest as possible probes of the history of the AGN itself, if it can be established that the onset of extensive star formation and the turn-on of the nucleus are roughly contemporaneous (admittedly a tall order, and a large question for the future). To explore the possibilities of learning the age and history of these "starburst disks", spectra of $\sim 1\text{\AA}$ resolution have been obtained for the $H\alpha$, $H\beta$, $[OIII] \lambda 5007$ regions in nuclei showing a range of activity and some evidence for surrounding star formation. The observations used the IPCS at the 2.5-m Isaac Newton Telescope on La Palma and CCDs at the INT and the Kitt Peak 4-m.

Figure 2 shows the $H\beta$ - $\lambda 5007$ regions approximately $16''$ SW of the nucleus of NGC 1068. This region has been studied in the UV by Weedman and Huenemoerder (1985), and shows HII-region emission in the images by Balick and Heckman (1985); a discrete near-IR source here also suggests a local clump of star formation (Telesco *et al.* 1984). The present data shows, in addition to narrow $H\beta$ emission from the HII region and broad $[OIII]$ associated with the nucleus (see the kinematic analysis by Alloin *et al.* 1983), stellar absorption features of $H\beta$, MgI , $H\gamma$, and the G-band. These features, and the Balmer emission diagnostic of the stellar Lyman continuum, have very different weightings with stellar age in an aging burst, and for a given burst model can serve as age or history diagnostics.

To illustrate this approach, consider a simple model of star formation with a Salpeter IMF turning on at some time and retaining a constant star-formation rate thereafter. INT blue spectra of the circumnuclear regions of NGC 1068 and 7469 may be roughly compared with such a model. In NGC 1068, $H\beta$ and $MgI \sim \lambda 5175$ are seen with equivalent widths of 7 and 3 \AA , while neither is detected in NGC 7469 at a level $\sim 2 \text{\AA}$. These data imply ages of $\sim 10^8$ and $< 10^7$ years, respectively. These are at least consistent with timescales needed to produce the extended ratio excess in each case (following de Bruyn and Wilson 1978). More detailed work, including more objects, emission-line results, and varying star forming histories, is in progress.

Star Formation in Markarian 231

The nucleus of Mkn 231 shows a number of unusual properties, including broad, blueshifted absorption, strong continuum reddening, and very strong IR emission (Adams 1972, Boksenberg *et al.* 1977, Rieke and Low 1972). The surrounding galaxy is also peculiar in morphology and spectroscopic properties and may be a nearby example of the conditions seen in, for example, 3C 48 (Boroson and Oke 1982). This section describes a study of the host galaxy of Mkn 231, conducted in collaboration with D. Hamilton (CTIO).

N1068 S 40-89

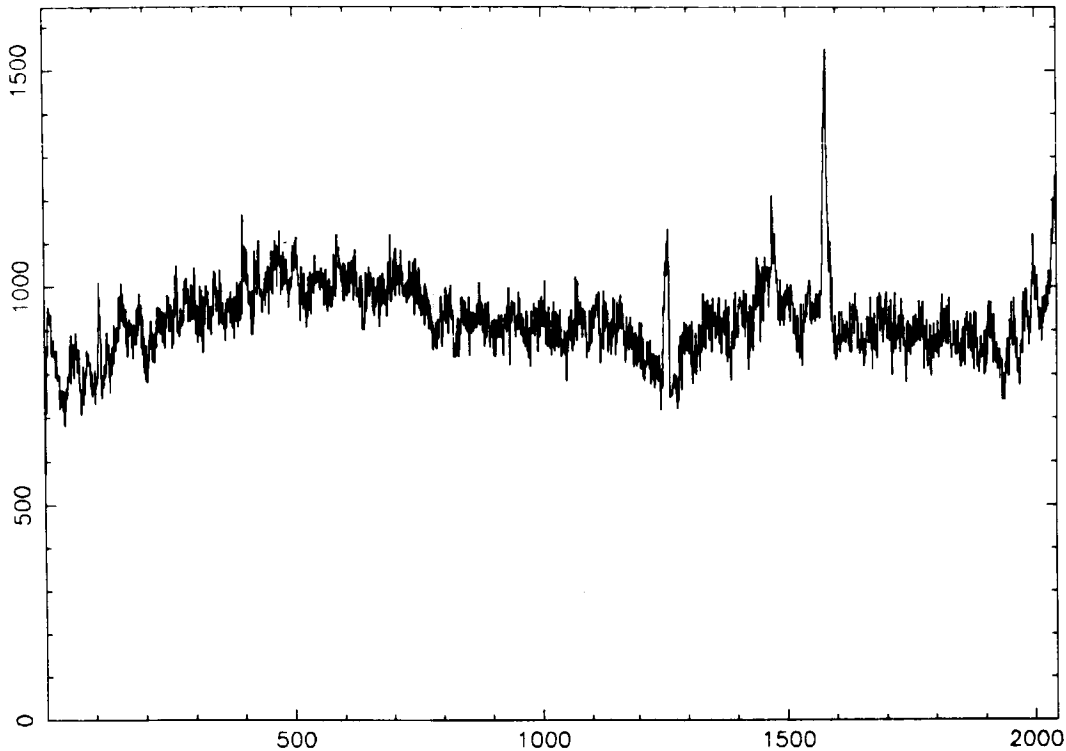


Figure 2. INT + IPCS spectrum in the 4300-5200 Å range, for the "starburst disk" of NGC 1068 16" SW of the nucleus. Stellar absorption of H β (a broad feature underlying the narrow emission line) is strong; other identifiable absorption lines include MgI, H γ , and the G-band. [OIII] emission redward (to the right) of H β , is mostly due to the effects of the Seyfert nucleus.

Multi-color imaging shows the galaxy to be very asymmetric, with smooth amorphous condensations and, at very faint levels, a pair of probable tidal tails. A large region of nearly constant surface brightness west of the nucleus offers a good opportunity to study the stellar population. A low-resolution spectrum of this region was obtained with the Cryogenic Camera at the KPNO 4-m, and shows relatively strong H β as well as MgI and MgH absorption, indicating a large contribution from stars of types A and F. In itself, this indicates active star formation within the last $\sim 5 \times 10^8$ years. However, the current star formation rate must be much smaller, as deduced from the lack of H α attributable to HII regions in the disk and lack of direct observation of such regions in H α images. Using the precepts of Kennicutt (1983), the SFR has dropped more than fourfold in this period.

It would be remarkable for a whole galaxy (of extent > 30 kpc) to turn off star formation everywhere in this time. The alternative is equally

remarkable, an IMF deficient in high mass stars. This is just the opposite of the case usually inferred for starburst galaxies. The stellar population here does appear similar to those in a few other active galaxies such as 3C 48 and 3C 459 (Miller 1981). The physics of star formation during galaxy mergers could provide important clues to what is seen here; Mkn 231 shows a pair of tails, and most giant radio galaxies, including 3C 459, show morphological or kinematic evidence of being merger products (Heckman *et al.* 1986). Mkn 231, at least, raises the possibility that conditions in some merging galaxies may favor formation of low-mass stars. If so, some interpretation of observations of many interacting and post-interaction systems would be much more complicated than previously thought.

Future Directions

The most pressing needs in understanding star formation around active nuclei are solid indications of how often, and at what levels, it occurs, and a detailed study of representative objects that could provide clues to the physical operation there. Schemes exist that could have a link between the phenomena going in either direction, or with both as a result of host galaxy properties. Weedman (1983) has considered the fate of condensed stellar remnants from a starburst; if they can reach a compact enough configuration, relativistic effects (Shapiro and Teukolsky 1985) could rapidly produce a single massive central object. Weedman notes that the process might be so rapid that both would be seen simultaneously.

In the other direction, active nuclei could induce surrounding star formations through shocks, perhaps via jets. There is clear evidence of jet-induced star formation on larger scales, in Cen A and Minkowski's Object (van Breugel *et al.* 1985, Brodie, Bowyer and McCarthy 1985, Graham and Price 1981). Finally as discussed for HII regions above, some kinds of potential might efficiently funnel gas both into kiloparsec and parsec scales, fuelling star formation and nuclear activity at the same time.

Surveys for extranuclear star formations might take several forms. IR colors (Rodriguez-Espinosa *et al.*, these proceedings) are relatively unbiased and reddening-free, but from the IRAS database it is not clear that the star formation is on a small enough scale to be connected with the nuclei. H α studies (imaging or slit spectroscopy) complement IR studies in spatial resolution, but can be of limited use when the nucleus is so luminous as to dominate the gas ionization at relevant distances within the disks. Finally, the work of Wilson *et al.* (these proceedings) suggests that radio morphology may be an additional useful diagnostic. All these kinds of surveys should be pursued.

More detailed studies of individual objects are in part available, and will continue as byproducts of studies of active nuclei.

Observations described here have been obtained at the Isaac Newton Telescope, now happily ensconced on the island of La Palma, and at Kitt Peak National Observatory and Cerro Tololo InterAmerican Observatory, National

Optical Astronomy Observatories, operated by A.U.R.A. under contract with the National Science Foundation. I am especially grateful to Susan Davidson for helping produce this manuscript on time.

REFERENCES

- Adams, T. F. 1972, Ap. J. (Lett.) **176**, L1.
 Alloin, D., Pelat, D., Boksenberg, A., and Sargent, W. L. W. 1983, Ap. J. **275**, 493.
 Balick, B. and Heckman, T. 1985, Astr. J. **90**, 197.
 Boksenberg, A., Carswell, R. F., Allen, D. A., Fosbury, R. A. E., Penston, M. V. and Sargent, W. L. W. 1977, M.N.R.A.S., **178**, 451.
 Boroson, T. A. and Oke, J. B. 1982, Nature, **296**, 397.
 Brodie, J. P., Bowyer, S. and McCarthy, P. 1985, Ap. J. (Lett.) **293**, L59.
 Cutri, R. M., Rudy, R. J., Rieke, G. H., Tokanuga, A. T. and Willner, S. P. 1984, Ap. J., **280**, 521.
 de Bruyn, A. G. and Wilson, A. J. 1978, Astr. Ap., **64**, 433.
 Graham, J. A. and Price, R. M. 1981, Ap. J., **247**, 813.
 Heckman, T. M., Smith, E. P., Baum, S. A., van Breugel, W. J. M., Miley, G. K., Illingworth, G. D., Bothun, G. D., and Balick, B. 1986, Ap. J. (in press).
 Hummel, G., van der Hulst, J. M., and Keel, W. C. 1986, Astr. Ap. (submitted).
 Keel, W. C. 1983, Ap. J. Suppl. **52**, 229.
 Kennicutt, R. C., Jr., 1983, Ap. J., **272**, 54.
 Miller, J. S. 1981, P.A.S.P., **93**, 681.
 Morris, S., Ward, M., Whittle, M., Wilson, A. S., and Taylor, K. 1985, M.N.R.A.S., **216**, 193.
 Rieke, G. H. and Low, F. J. 1972, Ap. J. (Lett.), **176**, L95.
 Sanders, R. H. and Huntley, J. M. 1976, Ap. J., **209**, 53.
 Sanders, R. H. and Tubbs, A. D. 1980, Ap. J., **235**, 803.
 Sersic, J. L. and Pastoriza, M. 1967, P.A.S.P., **79**, 152.
 Shapiro, S. L. and Teukolsky, S. A. 1985, Ap. J., **298**, 58.
 Telesco, C. M., Becklin, E. E., Wynn-Williams, C. G. and Harper, D. A. 1984, Ap. J., **282**, 427.
 van Breugel, W., Filippenko, A. V., Heckman, T. and Miley, G. 1985, Ap. J., **293**, 83.
 Weedman, D. W. 1983, Ap. J., **266**, 479.
 Weedman, D. W. and Huenemoerder, D. P. 1985, Ap. J., **291**, 72.

DISCUSSION

WILSON:

In our study of the circum-nuclear starburst in NGC 7469 (to be published in Ap. J. Nov. 1986), we do find evidence of H β absorption in some locations. Presumably, this would make the starburst somewhat older than you estimated.

KEEL:

This emphasizes an important issue in the study of these systems - spatial resolution and averaging. My data so far pertain only to limited slices through the circum-nuclear regions; since present star formation is obviously patchy, stars too young to have completely diffused will also have more or less 'lumpy' distributions. A more proper observational approach would involve mapping absorption features at many positions around the nuclei.